

Cosmological Origin of Quasars

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INTRODUCTION

Observations of high-redshift quasars and absorption systems provide a rich data set on the early formation of structure in the universe. Theoretical and observational investigation of the physics leading to the formation of quasars and their environments can shed some light on early structure formation. In this contribution, I summarize briefly a few aspects of quasar physics that are of cosmological interest.

ORIGIN OF QUASAR BLACK HOLES

The most recent evidence that massive black holes exist in the centers of galaxies comes from the existence of compact gaseous disks with high rotation velocities. Examples include the HST imaging and spectroscopic observations¹ of M87 that revealed a ~ 20 pc disk with a rotation velocity of ~ 500 km s⁻¹ and implied the presence of a $2 \times 10^9 M_\odot$ black hole, and VLBA observations² of the powerful water maser emission from a ~ 0.1 pc disk rotating at $\sim 10^3$ km s⁻¹ at the center of NGC 4258. In the latter case, the central mass density exceeds $4 \times 10^9 M_\odot$ pc⁻³ and is unlikely to be associated with anything other than a central black hole with a mass of $4 \times 10^7 M_\odot$. Independent observational constraints on the compactness of the energy source in active galactic nuclei come from unresolved lensed images (indicating³ a source size $\lesssim 1$ pc from HST imaging of the quasar 2237+0305), gravitational microlensing (indicating⁴ a continuum source of size $\lesssim 2 \times 10^{15}$ cm in 2237+0305), milliarcsecond jets (showing an unresolved core $\lesssim 10^{17}$ cm in some objects⁵), and rapid X-ray variability⁶.

The integrated light of quasars can be used to find the minimum mass density of black hole remnants today. This calculation⁷ implies that a fraction $\gtrsim 3 \times 10^{-5}$ of all the baryons in the universe have ended inside black holes. Formation of black holes must therefore be a non-negligible consequence of gravitational instability in the early universe, yet the origin of these $\sim 10^{6-10} M_\odot$ black holes in standard cosmologies is enigmatic⁸. In fact, most of the luminous mass in the universe is locked up in gas and stars that are prevented from condensing in the centers of galaxies by their angular momentum. A galaxy as a whole is a highly non-relativistic system which has a typical size that is $(v/c)^{-2} \sim 10^6$ times bigger than its Schwarzschild radius. Loeb & Rasio⁹ have performed hydrodynamic simulations of the collapse of protogalactic gas clouds and concluded that baryons are unlikely to reach a relativistic state

by merely sinking spontaneously to the center of a galaxy, unless a massive ($\gtrsim 10^6 M_\odot$) seed black hole is already in existence there. Without a massive seed, the rotationally-supported cold gas is strongly unstable to fragmentation due to its self-gravity, and is converted to stars long before it approaches relativistic scales. However, if a central massive seed is artificially added to the system, it could dominate gravity near the center and stabilize a smooth accretion disk of gas around it. The minimum seed mass necessary for that purpose, $\sim 10^6 M_\odot$, is consistent with the existence of a lower bound on the empirically determined black hole masses in active galactic nuclei. Various such determinations¹⁰ all yield black hole masses $\gtrsim 10^6 M_\odot$, with the lowest mass objects not necessarily being close to the detection threshold. Nevertheless, it is puzzling as to why a small fraction of the mass in the universe ended up in relativistic seeds while the rest was strongly prevented from doing so by its angular momentum. To answer this question, we must first consider the origin of angular momentum of collapsing systems in cosmology.

An initially overdense region in the universe that eventually forms a virialized object acquires angular momentum about its center of mass through tidal torques from its environment¹¹. It is therefore possible to imagine that different environments could result in different amounts of rotation for the final virialized object. As the initial conditions can be well-specified in terms of a Gaussian random field of density perturbations with some power-spectrum, one can calculate the distribution function of angular momenta for collapsed objects in the universe either numerically¹² or analytically^{11,13}. This distribution has a tail of low-spin objects which by chance happened to reside in an environment with a low tidal shear. When the analytical calculation is extended into the far low-spin tail of this distribution one finds an astrophysically interesting abundance of low-spin objects¹³. The cosmological collapse of low-spin systems is found to be close to spherical because of their spherical initial shape, and the low shear in their cosmological environment. In addition, because of the unusually low amplitude of the external shear, the gas in these systems is unlikely to be disrupted by external torques before it forms a compact disk. In more than $\sim 10^{-4}$ of the objects on the $10^6\text{--}10^7 M_\odot$ mass scale, the baryons can settle after the initial collapse and cooling phases to a compact disk of an initial size $\sim 10^{17}$ cm and a rotation velocity $\gtrsim 500$ km s⁻¹. Because of its small initial size, such a disk has a viscous evolution time $\lesssim 10^6$ yr, shorter than the characteristic time it takes a star or a supernova to form in it. The compact disk is therefore expected to evolve into a seed black hole¹³. Most of these seed black holes form just above the cosmological Jeans mass and have a mass $\sim 10^6 M_\odot$.

Each galactic bulge contains about $\sim 10^4$ subunits on the $10^6 M_\odot$ mass scale. Among these subunits there is a class of rare objects that are high density peaks which acquire low angular momentum during their cosmological collapse. These high peaks collapse early ($z \gtrsim 20$), long before any other

object in their nearby environment starts to form. Because of its low angular momentum, the gas in these rare peaks forms a deep potential well as it cools to a compact disk. The initial disk can then evolve to a massive black hole on a short viscous timescale ($\lesssim 10^6$ years), well before star formation or supernovae could act to disrupt it. After the bulge of the surrounding galaxy virializes, the already formed seed sinks to the center of the potential-well by dynamical friction. This process provides just the initial $10^6 M_\odot$ seed necessary to stabilize later accretion of gas around the center⁹. The later accretion allows the further growth of the black hole there. Qualitatively, the above sequence of events must take place at some level in the universe. The only open question is quantitative: *for a given power spectrum of initial density perturbations, what fraction of the 10^4 subunits belongs to this low-spin class?*

An analytical calculation of the distribution function of angular momenta¹³ shows that there is of order one low-spin subunit per bright galaxy, which is a $> 2.5\sigma$ peak with 10^{6-7} solar masses in gas and is capable of forming a black hole seed shortly after its initial cosmological collapse. In principle, it is also possible to get black hole binaries in galactic centers by the formation and sinking of more than one seed per galaxy. If more than two seeds sink to the center, slingshot ejection of black holes from the bulge becomes important.

It can be shown mathematically¹¹ that a high density peak on the $10^{6-7} M_\odot$ mass scale is very likely to be surrounded by a high density region on the $\sim 10^{10} M_\odot$ mass scale. Therefore, the seed black holes that form out of high peaks are very likely to be surrounded by galactic mass systems that collapse later and feed them with additional gas, thus resulting in the bright quasar activity¹³. The observed maximum in the comoving quasar density at $z \approx 2$ may just reflect the epoch of galaxy formation when considerable infall feeds these seed black holes¹⁴. The subsequent decline in the abundance of bright quasars at low redshifts would then result from the dilution of their gas supply. The lack of starlight around some nearby quasars¹⁵ may indicate that star formation does not necessarily precede the accretion process.

There are various observational ways to probe the above sequence of events. Searches for the progenitors of quasars at very high redshifts ($z \gtrsim 10$) may be best undertaken in the infrared or millimeter regimes; optical surveys are limited by intrinsic dust extinction or intergalactic absorption. The emission of fine-structure lines from the host systems of quasars can be detected by millimeter telescopes and provide information about the velocity dispersion and gas content of the hosts¹⁶. For example, the [C II] 158 μm line flux from a bulge surrounding a bright quasar at a redshift of 10 can reach ~ 2 mJy, and be detected at the 3σ level with a 1'' beam and a velocity resolution of 150 km s^{-1} after 40 minutes of integration by the future Millimeter Array telescope.

A novel method to set a lower limit on individual quasar lifetimes makes use of the Ly α forest¹⁷. It is well-known that the ionizing radiation from a

bright quasar can dilute the population of Ly α clouds in its vicinity out to a characteristic distance of $\sim 10^{7-8}$ light years¹⁸. When lines of sight separated by $\sim 1^\circ$ from the line of sight to the quasar are used to probe this “proximity effect”, they are sensitive to radiation that left the quasar $\sim 10^{7-8}$ years earlier than the radiation arriving from the quasar today. Therefore, two lines of sight can be used to set a lower limit on the quasar lifetime. By coincidence, this limit happens to be just in the regime of interest for the expected duty cycle of quasars¹⁴.

PROBING CLUSTERING AT HIGH REDSHIFTS THROUGH QUASAR ABSORPTION LINES

If quasars form in high density regions then they are likely to be surrounded by concentrations of galaxies. Groups and clusters of galaxies hosting a quasar can be found through the detection of Ly α absorption lines beyond the quasar redshift. The effect occurs whenever the peculiar velocities of the quasar and the Ly α clouds combine to lower the quasar redshift below that of its nearest Ly α cloud. For this to be observable, the distortion to the redshift distribution of Ly α clouds induced by the cluster potential must extend beyond the proximity effect of the quasar. For any specific cosmological model, it is possible to predict the probability for finding lines beyond the quasar redshift ($z_{\text{abs}} > z_Q$) under the assumption that the physical properties of Ly α clouds are not affected by flows on large scales (\gtrsim Mpc) in the quasi-linear regime. If quasars randomly sample the underlying galaxy distribution, the expected number of lines with $z_{\text{abs}} > z_Q$ per quasar can be as high as $\sim 0.25 \times [(dN/dz)/350]$ at $z = 2$ for Cold Dark Matter cosmologies, where dN/dz is the number of Ly α lines per unit redshift far from the quasar¹⁹. The probability is enhanced if quasars typically reside in small groups of galaxies. In addition, a statistical excess of Ly α lines is expected near very dim quasars or around metal absorption systems. The expected magnitude of these clustering effects should be detectable by forthcoming observations with the Keck telescope. Finally, it can be shown¹⁹ that the standard approach to the proximity effect overestimates the ionizing background flux at high redshifts by up to a factor of ~ 3 , as it ignores clustering. This result weakens the existing discrepancy between the deduced background flux and the contribution from the known population of quasars.

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